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Fuzzy-stochastic-based violation analysis method for planning water resources management systems with uncertain information

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ABSTRACT

In this study, a fuzzy-stochastic-based violation analysis (FSVA) approach is developed for the planning of water resources management systems with uncertain information, based on a multistage fuzzy-stochastic integer programming (FSIP) model. In FSVA, a number of violation variables for the objective and constraints are allowed, such that in-depth analyses of tradeoffs among economic objective, satisfaction degree, and constraint-violation risk can be facilitated. Besides, the developed method can deal with uncertainties expressed as probability distributions and fuzzy sets; it can also reflect the dynamics in terms of decisions for water-allocation and surplus-flow diversion, through transactions at discrete points of a complete scenario set over a multistage context. The developed FSVA method is applied to a case study of water resources management within a multi-stream, multi-reservoir and multi-period context. The results indicate that the satisfaction degrees and system benefits would be different under varied violation levels; moreover, different violation levels can also lead to changed water-allocation and surplus-flow diversion plans. Violation analyses are also conducted to demonstrate that violating different constraints have different effects on system benefit and satisfaction degree.

1. Introduction

There are two major types of methodologies for tackling uncertainties existing in decision making problems: fuzzy mathematical programming (FMP) and stochastic mathematical programming (SMP). FMP is effective in dealing with decision problems under fuzzy goal and constraints and in handling ambiguous coefficients of objective function and constraints caused by imprecision and vagueness [2,10,15,26,28,37,42,46,47]. SMP is an extension of mathematical programming to decision problems whose coefficients (input data) are not certainly known but could be represented as chances or probabilities [3,6,16,17]. Among the SMP methods, scenario-based stochastic programming with recourse is effective for decision making problems where an analysis of policy scenarios is desired and the related data are random with known probability distributions [23].

In the past decades, a number of FMP methods were developed for dealing with uncertainties presented as fuzzy sets in water resources management [8,13,21,22,25,34,39,44,45]. For example, Russel and Campbell [36] used fuzzy logic analysis for supporting the operation of a hydroelectric reservoir system. Teegavarapu and Simonovic [40] proposed reservoir loss functions for a reservoir operation problem through using fuzzy set theory concepts, where membership functions were

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Nomenclature

f	expected net system benefit over the planning horizon (\$)
t	time period, $t = 1, 2, \ldots, T$
K_1^t	numbers of possible scenarios for stream 1 in period t
K_2^t	numbers of possible scenarios for stream 2 in period t
p_{tk_1}	probability of occurrence of scenario k_1 (for stream 1) in period t
p_{tk_2}	probability of occurrence of scenario k_2 (for stream 2) in period t
NB_t	net benefit per unit of water allocated in period t (\$/m^3)
PE_t	penalty per unit of water not delivered in period t (\$/m^3), and $PE_t > NB_t$
FC_t	fixed-charge cost for surplus-flow diversion in period t (10^6)
VC_t	variable cost for surplus-flow diversion in period t (\$/m^3)
$W_{tk_1k_2}$	amount of surplus-flow to be diverted in period t under scenarios k_1 and k_2(m^3)
X_t	water-allocation target that is promised to the municipality in period t (m^3)
$Y_{tk_1k_2}$	shortage level by which the water-allocation target is not met associated with joint probabilities of $p_{tk_1}p_{tk_2}$(m^3)
$Z_{tk_1k_2}$	binary variables for identifying whether a surplus-flow diversion action needs to be undertaken in period t under scenarios k_1 and k_2.
A_1^0	storage-area coefficient for reservoir 1
A_2^0	storage-area coefficient for reservoir 2
A_1^a	area (per unit of active storage volume) above A_1^0
A_2^a	area (per unit of active storage volume) above A_2^0
e_{1t}	average evaporation rate for reservoir 1 in period t
e_{2t}	average evaporation rate for reservoir 2 in period t
S_{tk_1}	storage level in reservoir 1 in period t under scenario k_1(m^3)
$S_{tk_1k_2}$	storage level in reservoir 2 in period t under scenarios k_1 and k_2(m^3)
$\widehat{Q_{tk_1}}$	random inflow into stream 1 in period t under scenario k_1(m^3)
$\widehat{Q_{tk_2}}$	random inflow into stream 2 in period t under scenario k_2(m^3)
R_{tk_1}	released flow from reservoir 1 in period t under scenario k_1(m^3)
$R_{tk_1k_2}$	released flow from reservoir 2 in period t under scenarios k_1 and k_2 associated with joint probabilities of $p_{tk_1}p_{tk_2}$(m^3).
RSC_1	storage capacity of reservoir 1 (m^3)
RSC_2	storage capacity of reservoir 2 (m^3)
RSV_{1t}	reserved storage level for reservoir 1 (m^3)
RSV_{2t}	reserved storage level for reservoir 2 (m^3)
$De_t^{\min}$	minimum water demand of the municipality in period t (m^3)
$De_t^{\max}$	maximum water demand of the municipality in period t (m^3)
$M_{tk_1k_2}$	variable upper bound for surplus-flow diversion in period t under scenarios k_1 and k_2, and is assumed to be sufficiently large

used to represent the decision maker's preferences in the definition of shape of loss curves. Bender and Simonovic [4] proposed a fuzzy compromise approach for the planning of water resources systems under uncertainty; it allowed a family of possible conditions to be reviewed, and supported group decisions through fuzzy sets designed to reflect collective opinions and conflicting judgments. Jairaj and Vedula [20] optimized a multi-reservoir system through using fuzzy mathematical programming method, where uncertainties existing in reservoir inflows were treated as fuzzy sets. Ben Abdelaziz et al. [5] developed a fuzzy chance-constrained goal programming approach for a reservoir operation problem, where uncertainties were treated as fuzzy sets and probabilities. Mujumdar and Sasikumar [31] developed a fuzzy optimization model for the seasonal water quality management of river systems, where the occurrence of low water quality was treated as a fuzzy event and randomness associated with the water quality indicator was linked to this fuzzy event using the concept of probability of a fuzzy event. El-Baroudy and Simonovic [12] proposed three new fuzzy reliability measures for reliability analysis of water resource systems; they included (i) a combined reliability-vulnerability index, (ii) a robustness index, and (iii) a resiliency index. Akter and Simonovic [1] proposed a multiobjective programming model based on the fuzzy set theory and fuzzy logic for flood management in the Red River Basin, Canada; three stakeholder inputs, including scale (crisp), linguistic (fuzzy), and conditional (fuzzy), were analyzed to obtain aggregated inputs expressed as fuzzy expected values. Teegavarapu and Elshorbagy [41] proposed a fuzzy mean squared error measure to evaluate the performance of time series prediction models in water resources, where membership functions derived from a number of modeler preferences could be easily aggregated to obtain a single integrated membership function. Nasiri et al. [32] proposed a fuzzy multiple-attribute decision support expert system for dealing with the uncertainties surrounding water quality index making problem. Nevertheless, the main limitations of the FMP methods remain in their difficulties in tackling uncertainties expressed as probabilistic distributions in a non-fuzzy decision space.